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Annual Progress Report

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31 January 1982

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A summary is presented of research activity for the period 1 Dec 80 through 30 Nov 81 performed under AFOSR Contract F49620-79-C-0010 at Stanford University by Professors S J Kline, J H Ferziger, J P Johnston and R J Moffat. Recent progress is described in two principal areas: the prediction of turbulent flow in straight wall diffusers, with and without separation, and the study of convective heat transfer on cacave surfaces.

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Annual Status Report, 3/1/82
Contract AFOSR [redacted]-F49620-79-C-0010

"Theoretical and Empirical Studies of the Basic Structure of Turbulent Shear Flows, Including Separated Flows and Effects of Wall Curvature"

2. Work Area

Part I: Separated Flows, Detachment and Reattachment; Diffuser Computation Methods

Principal Investigator, Part I: Prof. S. J. Kline
Co-principal Investigator, Prof. J. H. Ferziger

Introduction and Approach

Work under this contract employs experiments, correlations, and computations to investigate separating, separated, and reattaching flows, including flow in diffusers. When critical to research needs, new instruments and procedures are devised. The work is a major part of an integrated program in long-range research on turbulent shear flows (called HTTM). The AFOSR contract benefits strongly from interaction with other parts of the program. The total program is designed to cover several forefront areas in experimental work, instrumentation, and three levels of computation: zonal, Reynolds-stress-equation modeling, and large-eddy simulation. Earlier work and work planned for later portions of the current contract also emphasize study of structure and production of turbulence in shear layers. Research focuses on central long-range problems, and, wherever possible, carries work up to the point where it can be transferred into industrial applications. For example, diffuser flows have been studied from several viewpoints. The flow regimes were classified and mapped some years ago in what are now the standard design charts. In current work under this contract, very successful and very rapid programs for computing such flows have been developed and are already in use in industry. Extensive written discussion on computation of diffuser flows and on the "physics of diffuser flows" is contained in four reports and two papers completed during the past year (see below). A second major area of effort under this contract concerns turbulent boundary layers on concave walls. This work supplements and is supplemented by similar work on convex walls under NASA-Lewis lab support.

3. Status of Research Effort:

General Remark on Diffuser Computation. Prior to 1980, our group had successfully developed a new method of computing turbulent boundary layers that are approaching separation, separating, or separated. This is an integral method which relies for its success on the introduction of new shape factors for the boundary layer and on improved correlations for detachment, entrainment, skin friction, and reattachment. The method has proven to be both very fast and very accurate. It was therefore applied to the computation of diffuser flows. With the diffuser core represented as a one-dimensional flow, it was found that this method is capable of predicting diffuser performance in the unstalled, transitory stall, and full stall regimes; extension to the jet flow regime is possible.

The 1979-80 year was a period of very rapid advance, with various earlier works collecting into finished codes. The existing codes were brought to the stage of practical design tools that can be used in industry, but still needed to be unified and more thoroughly connected in order to facilitate industrial use. These 1979-80 results are repeated below since much work in the 1980-81 period was concerned with preparation of reports covering this work. The various codes cover planar, conical and various annular types; they also cover compressible flows to $M = 0.9$, and diffusers with unsteady free streams. The codes are not only very fast but give results in essential agreement with the entire range of known data for all but a few points involving special conditions, as noted below. Moreover, when output is compared to the most accurate data, as for example those of R. L. Simpson and co-workers or Ashjaee and Johnston, agreement is significantly better. Overall, we believe we have largely closed up practical computations of diffusers with straight centerlines. Strongly curving cases remain for future work. Some questions also remain regarding high-turbulence core cases.

More specifically, the following developments took place during the 1979-80 year. All work described was supervised by Professors Kline and Ferziger; the students who were responsible for the various components of the work are listed below.

a. A new entrainment correlation was developed. The new correlation was as accurate as the old, widely used, Bradshaw correlation. However, it provided entrainment explicitly in terms of the shape factor for the boundary layer and was therefore both easier to program and much faster in operation. Use of this new correlation speeded up the diffuser program considerably, and, more importantly, it made feasible the unsteady boundary layer method and the inverse method of diffuser computation described below. (A. Lyrio, J. Bardina)

b. A new skin friction correlation was developed. This correlation is at least as accurate as the ones which were used previously; however, it is explicit and therefore easier to use. It also has the important advantage that it is applicable after separation. This correlation is now a standard component of our diffuser program. (A. Lyrio, J. Bardina)

The method developed for the computation of planar diffusers was extended to the annular and conical configuration. This involved the adaptation of the boundary layer method to the axisymmetric case and the introduction of a one-dimensional, axisymmetric core. The method developed is as accurate as the planar diffuser method. (A. Lyrio, J. Bardina)

d. The boundary layer method was extended to flows with unsteady free stream. This turned out to be surprisingly simple. We found that almost all of the correlations used in the steady case can be employed. The method has been used to predict all known unsteady boundary layer data; agreement of predictions with data is again within the uncertainty bands. The only exceptions are some discrepancies in the one available data set that includes separation. Because the data for such flows are scant; further study is needed on both experiments and theory. (A. Lyrio)

e. The unsteady method described in (d) above was used to construct a code for predicting the unsteady behavior of diffusers. In particular, we have been able to predict the data by Schachenmann and Rockwell and by Cousteix and Houdeville on diffusers with unsteady inlet conditions within the uncertainty of the data. These comprise all the known data sets. There are discrepancies at the exit plane in the data of Cousteix and Houdeville. It is not clear whether the difficulty lies in the experiment or in the computation. (A. Lyrio)

f. An analysis of the singularities in the equations describing turbulent boundary layers was performed. It is well known that these equations become singular in the neighborhood of detachment. We analyzed the behavior of several possible boundary layer methods with prescribed pressure gradient and showed that, indeed, any combination of equations becomes singular near incipient detachment (not full detachment) in a prescribed pressure computation. However, when a single boundary layer is allowed to interact appropriately with an internal core flow or an external potential flow, the singularity can be shifted in such a way that it no longer lies in the domain of computation. This analysis has played an important role in helping to develop the method of computing internal flows with the asymmetric boundary layers which is described in item "g" below. (R. Childs)

g. A method of dealing with diffusers with asymmetric boundary layers was developed. In the transitory and fully developed stall regimes, the stall is nearly all on one wall. The method of Bardina and Lyrio treats the diffuser as symmetric and includes a correction for the curvature near separation. The Bardina/Lyrio method could not treat asymmetric boundary layers, because the equations become singular when two boundary layers are included. The difficulty was corrected by interacting the separating boundary layer strongly with the core and treating the unseparated boundary layer as weakly interacting. This method proved successful and is now fully tested. This advance in the understanding of the singular behavior was an important step toward computation of detachment in strongly curving passages. See comment under 1980-81 below. (R. Strawn)

h. An inverse or "stall margin" method of computing diffuser flows was developed. In this method, the user specifies the distance of the boundary layer from detachment (in terms of shape factor) as a function of the downstream coordinate; the program then predicts the geometry of the diffuser. The method is based on the correlations used in the codes described in items (a) through (d). It has been tested against known diffusers with good success for both planar and conical geometries. The method predicts that substantial improvements in diffuser design are possible for short diffusers with small inlet blockage and low inlet $H = \delta^*/\theta$. Smaller or negligible benefits are obtained in other cases. The results appear reasonable, and we recommend that at least some of the proposed designs be tested. (R. Strawn)

i. Considerable further advance was realized in our understanding of the processes of flow detachment and its correlation. The basic correlation was reported in the work year 1978-79. During the work year 1979-80, we obtained further data using new instrument techniques developed in HTTM, and consolidated this understanding. We came to realize that all earlier results both for detachment correlation and with regard to singular behavior of the computing equations have suffered from basic confusion on a single point: the failure to distinguish incipient detachment from full detachment. This confusion in turn rests on the failure to understand the fundamental difference in the physics between a steady laminar detachment and a turbulent detachment on a faired surface. A steady laminar detachment is a location where the velocity gradient dU/dy is zero and hence the wall shear is continuously zero. A turbulent detachment is a location where the wall shear is zero only on the average, an average composed of significant transient values of shear both positive (downstream) and negative (upstream). The laminar, steady detachment occurs along a sharp line. The turbulent detachment is a region or zone that may be either short or long in the flow direction, depending on the circumstances. These differences have important practical implications in the correlation of data, and hence in computation. Study of past visual data shows that the visual methods all indicate incipient rather than full detachment. Similarly, a study of past correlations and criteria for detachment of the turbulent boundary layer shows that the first occurrence of singular behavior in the equations is associated with incipient rather than full separation in marching schemes employing prescribed pressure distributions. This result is general, as can be seen from the fact that all 28 methods in the 1968 AFOSR-IFP-Stanford Conference on Computation of Turbulent Boundary Layers run into problems (and either fail or require ad-hoc fixes) well upstream from full detachment. Our singularity analysis, item (f), provides the reasons for these results in computation.

We have constructed an excellent correlation for incipient detachment of turbulent boundary layers. Thus we know when it is necessary to be careful concerning the possibility of singular behavior, and when to shift correlations from standard attached layer forms to detaching or detached forms. This information is well enough understood to be programmed. The same information is used as the basis for our "stall margin metric" and for specifying the shapes of optimum contoured wall diffusers with straight centerlines. The problem of optimum contouring has been attempted earlier by several other groups; however, we believe the boundary layer computation methods available to those groups were not of sufficient accuracy to settle the problem. We believe the methods reported above do have the requisite accuracy.

j. Work on reports during 1980-81. Because so many new results came to completion in the 1979-80 work year, much of the effort during 1980-81 was involved with preparing reports and papers on this work. Four reports and two papers were prepared.

One paper covers the new correlation and understanding of detachment of a two-dimensional turbulent boundary layer. The paper was presented as AIAA preprint 81-1200 at the meeting in Palo Alto in June and will be published in the AIAA Journal. We believe it is an important advance on this topic. See Reference I-1.

The second paper covers the work on the inverse (stall margin) method for computation of diffusers. It has been submitted to the Journal of Fluids Engineering for possible publication.

Because the four reports (Ref. 7-10 below) cover some twelve closely related but somewhat different computer programs, we have also prepared a unified, more fully documented program for dissemination to industrial users. At the end of the 1980-81 work period, this program had been largely completed.

k. Work on the backward-facing step and reattachment during 1980-81.

Experimental studies on the reattaching flow behind a backward-facing step continued in the flow-visualization water channel. Extensive visualization using hydrogen bubbles has been performed, resulting in improved understanding of the physical structure of the flow. The initial region of the shear layer has been observed to possess a structure similar to that observed in a two-dimensional mixing layer. The reattachment region itself appears to be characterized by three-dimensional, unsteady motion generated as the structures in the shear layer strongly interact with the wall. Detailed study of the films obtained is still under way.

Methods of obtaining quantitative data to supplement the visualization results are also being developed. The thermal tuft, an instrument developed at Stanford to measure instantaneous flow direction in a reattaching flow, has previously been used only in air flows. In the past year, its use has been extended to water flows, and it was used in mapping the reattachment region for the geometry being used in the flow-visualization studies. The tuft was also used to measure the change in the reattachment region produced by varying the angle of the step wall. This angle was varied from 0 to 4°, in the direction which produces a stronger adverse pressure gradient in the flow. The result was a substantial increase in the reattachment length.

The ability to acquire quantitative data in the water channel will be greatly enhanced by the use of a two-component laser-doppler anemometry system to obtain profiles of velocity and turbulent stresses. The laser system has been installed in the channel, and a positioning system for the precise movement needed to obtain the desired profiles has been constructed. Alignment of the laser and the creation of the software necessary to obtain data are under way, and the first attempts at measurements will be made in the near future.

ℓ. Computation of detaching and detached flows in strongly curved passages. As reported earlier, the computation of these flows presents two problems beyond the scope of the successes reported above for diffusers with straight centerlines. First, the presence of cross-stream variation velocity makes use of one-dimensional core approximations inappropriate. Moreover, the introduction of two-dimensional core procedures creates new kinds of problems in the viscid-inviscid matching procedures. A second problem arises from the change in turbulence production and boundary layer development on curved walls. The second problem is the focus of Part II of this program and is still under relatively early study insofar as concave walls are concerned. Hence, in 1980-81, work on computation of curved channels concentrated on the problems of viscid-inviscid matching. Early successes, reported in the 1981 status report, did not extend to cases with large amounts of separation. Convergence became slow and, in some methods, difficulties with the downstream boundary conditions occurred. At the end of the work year reported, a new method was being developed that appears to have considerable promise in solving these problems and reducing computer times by an order of magnitude for such problems. This is an averaged or "collocative" matching procedure that appears to be new. Effort in developing and checking the procedure will continue in 1981-82.

Reference

1. Kline, S. J., J. Bardina, and R. C. Strawn, "Correlation and Computation of Detachment and Reattachment of Turbulent Boundary Layers on Two-Dimensional Faired Surfaces," AIAA-81-1220, presented at the 14th AIAA Fluid and Plasma Dynamics Conference, Palo Alto, CA, June 1981, to be published in AIAA Journal.

Annual Status Report, 3/1/82
Contract AFOSR AF-F-49620-79-C-0010

"Theoretical and Empirical Studies of the Basic Structure and Properties of Turbulent Shear Flows"

2. Work Area (contd.)

Part II: The Heat Transfer and Fluid Dynamics of Concave Surface Curvature

Principal Investigators: James P. Johnston and Robert J. Moffat

Preface

There is ample evidence that convective heat transfer on a curved surface is significantly different from that on a flat surface--lower on a convex surface and higher on a concave surface. These effects are controlled by the fluid mechanic behavior and must be studied in that context. Curved surfaces exposed to high heat loads occur in many power systems of interest to the Air Force and are frequently the most vulnerable components of a system, e.g., nozzles in rockets and ramjets, blades and vanes in gas turbines, and all curved internal flow passages. The fluid mechanic mechanisms by which heat-transfer augmentation occurs have been postulated, but as of the present time there is no firm experimental evidence that these hypotheses are correct. Accurate prediction of heat transfer on the curved surfaces requires a proper understanding of the fluid mechanics involved. The discrepancy between curved- and flat-surface heat transfer may be as large as ± 40%, which is well beyond the safe margin in many designs.

Introduction and Approach

Heat transfer on a concave surface is significantly higher than on a flat surface, other factors being equal. The present program is aimed at determining the mechanism responsible for this increase and the means of predicting its occurrence. The approach is to construct a flow-visualization and heat transfer experiment which allows simultaneous visualization of the flow structure and measurement of heat transfer rates. The studies are being conducted in a newly fabricated water test facility built expressly for this program.

Several workers have suggested that a basic flow instability leading to longitudinal roll cells called Taylor-Gortler cells is responsible for the increase of mean surface stress and heat flux. The flow structure is being made visible and recorded by photographic and television means to check this suggestion. A synchronous stop-motion TV system has been purchased which can be carried on a carriage at the mean fluid speed. This allows the evolution of the boundary layer structure to be studied in detail, using a frame of reference moving with the mean fluid speed. The heat transfer will be made visible and quantitatively evaluated by a new liquid-crystal technique developed at Stanford. Recent work has shown that an electrically heated liquid crystal film can be used to make visible a line along which the heat transfer coefficient, h, is constant. This technique had previously been developed and demonstrated in air, and has now been adapted to water studies for the current program.

A. Hydrodynamic Studies

Following the dye flow-visualization reported last year, extensive surveys of the turbulent boundary layer flow over a concave wall were completed using combined hot-film anemometer and hydrogen bubble visualization. The velocity data obtained serve to qualify the apparatus and reveal some of the features of the flow field. The hydrogen-bubble visualization demonstrated the presence of large-scale, randomly distributed sweeps and ejections which appear to control the development of the turbulence structure of the flow field. These large-scale structures are not seen in flat-wall boundary layers and seem to suppress turbulence production near the wall while increasing it in the outer flow.

Status Report

This research program has been under way for about three years. The first year was spent constructing a large-scale water channel specifically designed to carry out the proposed studies. In the following year, the channel was made fully operational, and dye-visualization studies were carried out. During the past year, we have made extensive measurements of mean velocity and turbulence intensity throughout the flow field and have obtained detailed visual records of the flow using the hydrogen-bubble technique.

Velocity profiles were obtained using a DEC MINC-11 microcomputer to control the position of the hot-film probe and to acquire the data. The low velocities encountered in the channel (15 cm/s or less) necessitated long averaging times, typically six minutes per data point. Under normal circumstances, temperature drift and probe contamination would have had to be closely controlled in order to use hot films. With the probe under computer control, however, we were able to avoid these problems. Prior to each measurement, the probe was moved to a fixed reference location in the free stream. The anemometer bridge output obtained there was then used to normalize readings in the boundary layer. In this way, we were able to remove the effects of temperature drift and slow changes in the channel flow rate. In addition, the frequent movement of the probe dislodged dirt particles on the probe and kept the long-term calibration steady. The computer also eliminated the need for a linearizer; bridge voltages were converted directly to velocities using a look-up table stored in the computer.

Some of the results of the velocity measurements are shown in Figs. II-A1 through II-A2. The concave test wall channel geometry is defined in Fig. II-A1. Figure II-A2 shows spanwise profiles of mean velocity and turbulence intensity taken 30° into the curve, while Fig. II-A3 shows the streamwise development of boundary layer profiles. Both these profile sets will be discussed below in conjunction with the visualization results. Integral parameters for the flat wall upstream of curvature are shown in Table 1. The parameters in Table 1 were calculated by fitting a Coles Law of the Wall and Wake to the data, following the procedure described in Coles & Hirst (1969). Values of the integral thicknesses appear to be particularly sensitive to scatter in the data. The friction velocity u_τ may be a better gauge of spanwise uniformity. A slight spanwise gradient is indicated in Fig. II-2 and Table 1, but over the region $z = \pm 10$ cm the uniformity of the flow appears acceptable for the purposes of the current study.

Table 1

SPANWISE VARITION OF BOUNDARY LAYER PARAMETERS, $X = 400$ cm

Z cm	δ^* cm	θ cm	δ^*/θ	U_τ cm/s	Re_θ	c + 1 0.001	Data Set
20	1.176	0.826	1.423	0.675	1349	4.164	QUAL3
10	1.122	0.782	1.434	0.676	1282	4.146	QUAL1
0	1.160	0.814	1.426	0.686	1360	4.101	FLAT1
0	1.057	0.734	1.440	0.684	1206	4.222	FLAT2
0	1.170	0.815	1.137	0.666	1428	3.979	FLAT5
-10	1.046	0.729	1.433	0.688	1200	4.259	QUAL2
-20	0.931	0.648	1.436	0.702	1066	4.434	QUAL7

A detailed visual survey of the flow was performed using hydrogen bubbles. Some representative views are shown in Figs. II-A4 and II-A5. The views shown are negative images printed from motion picture footage. The flow is predominantly out of the page and slightly tilted towards the lower left-hand corner. The numbers on the right, along with the dotted lines, indicate distances of the bubble wire from the wall in centimeters, e.g., the mean streamwise location of the bubbles at their origin. Fig. II-A4 was taken upstream of the curve at $x = 330$ cm, while Fig. II-A5 was taken 50° into the curve. Note the presence of large-scale motions in the latter, compared to the flat-wall case, Fig. II-A4. The motion pictures obtained show that the large-scale sweeps and ejections which dominate the flow in the curve suppress the usual bursting process near the wall, while producing new turbulence in the outer flow. The sweeps and ejections are of limited streamwise extent, are randomly distributed, and are convected downstream. They closely resemble the structures seen by Johnston et al. (1972) in a rotating channel flow (Ref. A-2).

The visual results make interpreting Fig. II-A3 easier. The fuller velocity profiles are a result of the large-scale mixing caused by the large-scale sweeps and ejections. The interaction between the ejections and the outer flow increases the turbulence intensity away from the wall. Although bursting near the wall is diminished, the turbulence intensity there remains high due to contributions from the large scales and convection of small scales toward the wall by the sweeps. The spanwise profiles in Fig. II-A2 demonstrate that the large-scale motions are truly random; they are not fixed in position, as has been reported by previous investigators.

A 12-minute motion picture has been produced which summarizes the visualization done in the turbulent flow field.

References

II-A1 Coles, D. E., and Hirst, E. A., eds., Computation of Turbulent Boundary Layers--1968 AFOSR-IFP-Stanford Conference, Vol. II. Thermosciences Div., Dept. of Mech. Engrg., Stanford Univ., Stanford, CA 94305 (1969), pp. 1-17.

II-A2 Johnston, J. P., Halleen, R. M., and Lezius, D. K., "Effects of Spanwise Rotation on the Structure of Two-Dimensional Fully Developed Turbulent Channel Flow," J. Fluid Mech. (1972), Vol. 56, Part 3, pp. 533-557.

Publications in Progress

"The Effects of Concave Curvature on Turbulent Boundary Layer Structure," by A. Jeans and J. P. Johnston.

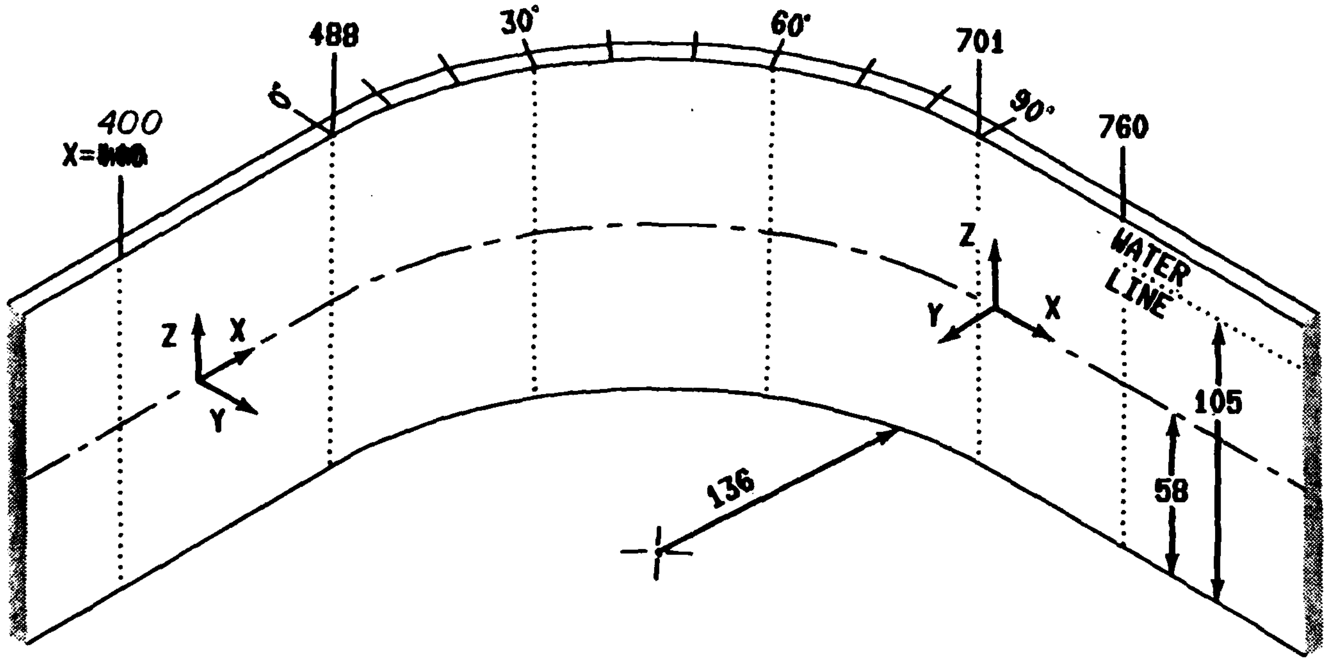

Figure II-A1: Concave test wall, dimensions in centimeters.

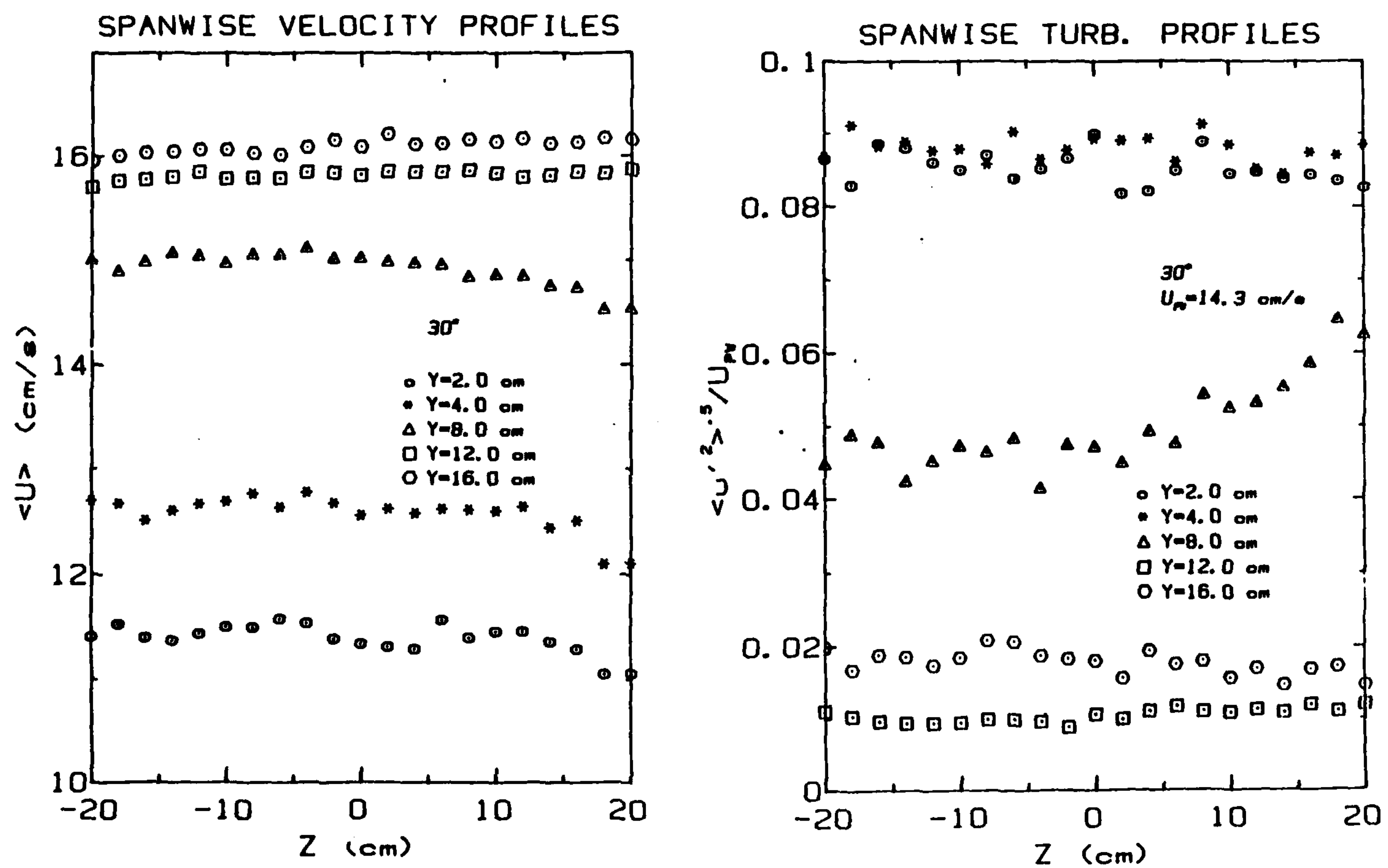

Figure II-A2: Spanwise profiles at 30°.

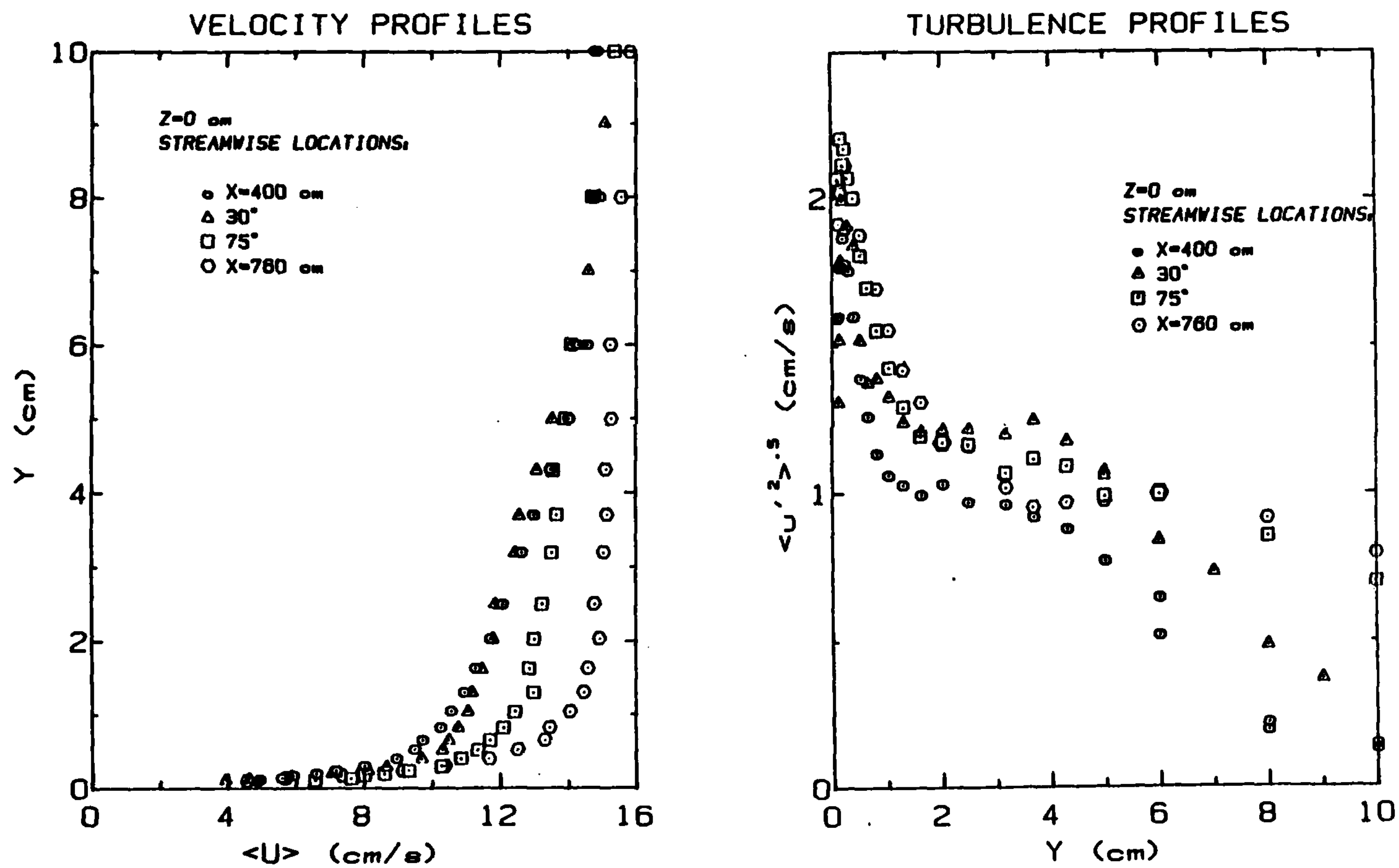

Figure II-A3: Streamwise development of velocity and turbulence intensity profiles.

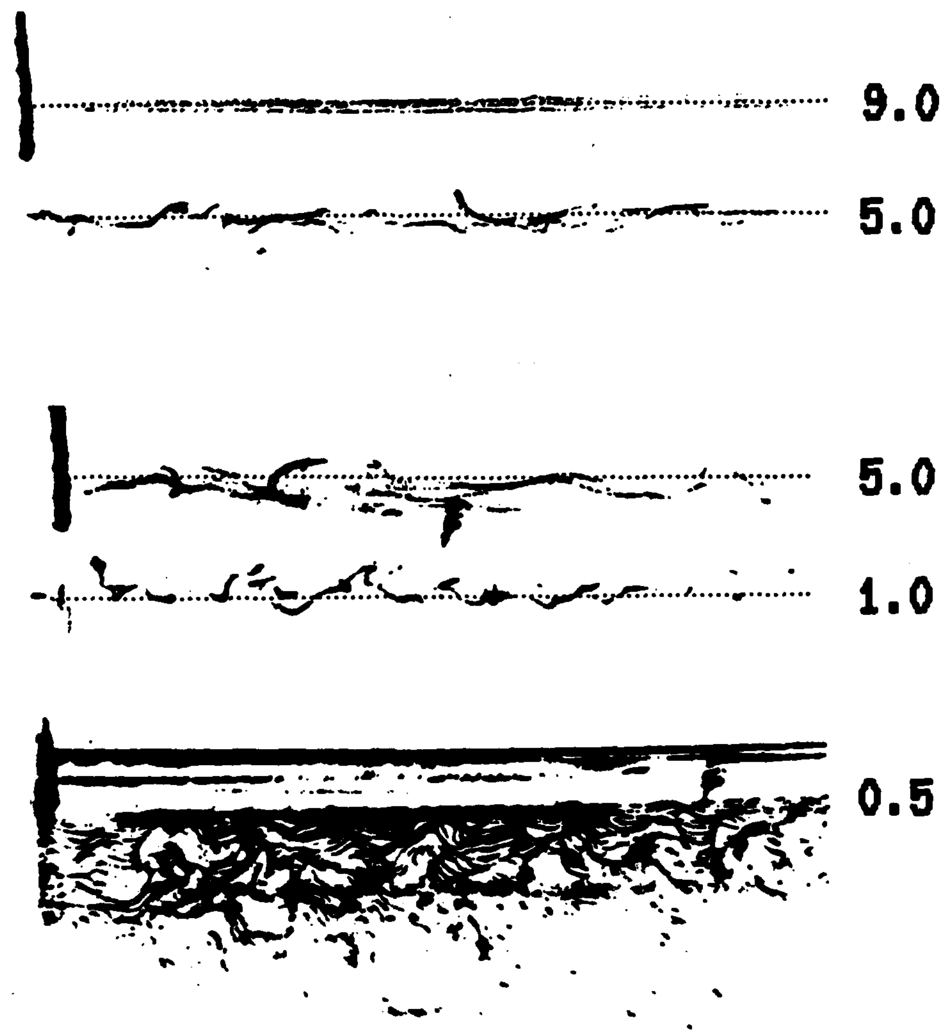

Figure II-A4: x = 440 cm, inlet.

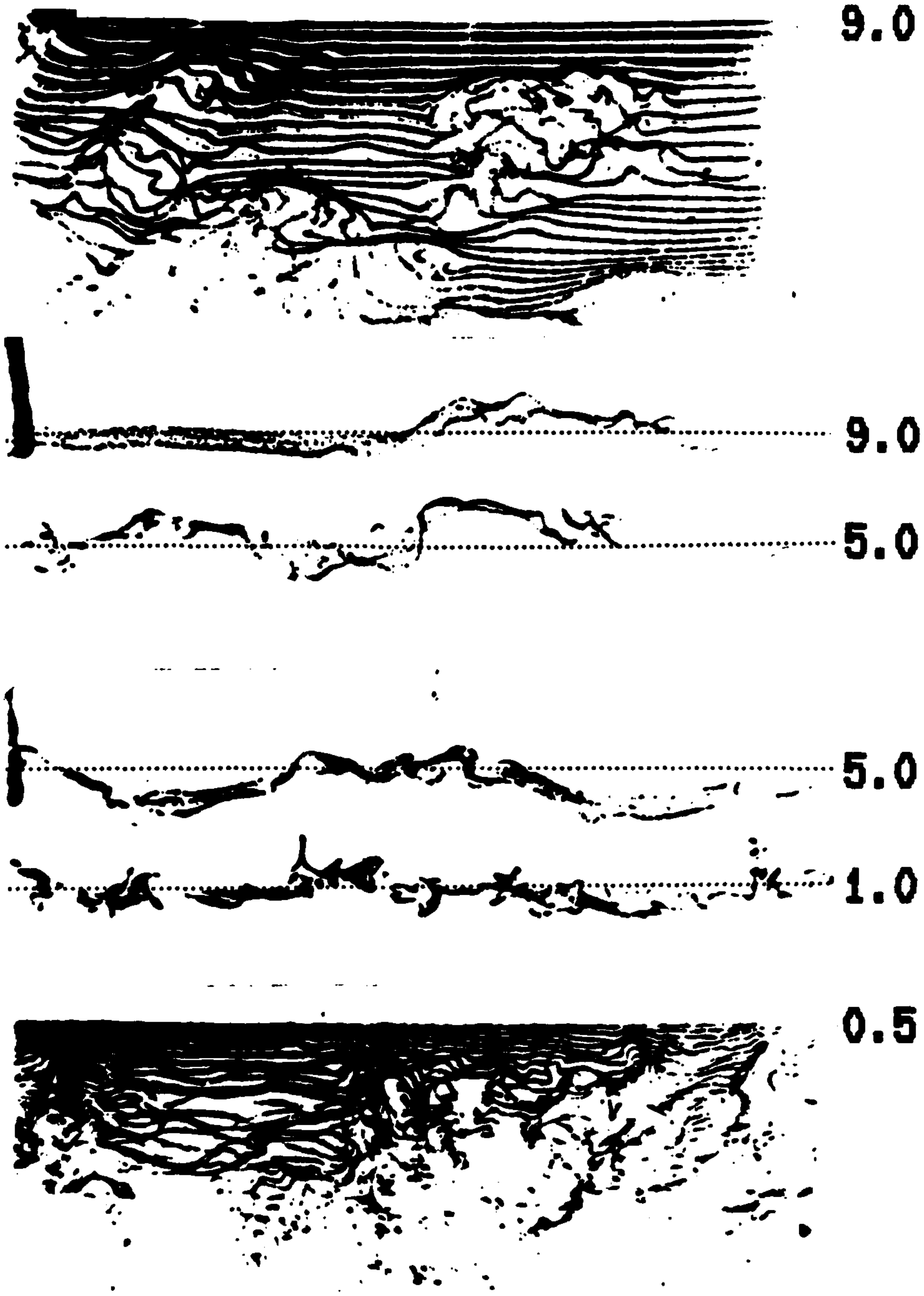

Figure II-A5: 50°

3. Status of Research, Part II (cont.)

B. Heat Transfer from a Turbulent Boundary Layer on a Wall with Strong Concave Curvature

Introduction

In the first year of the project, most of the effort was spent designing and building the main facility. In the second year, a considerable amount of time was spent designing, developing, and qualifying the liquid crystal technique. The past year has seen the technique qualified as a useful heat transfer measurement technique. The method has been qualified in laminar free convection, laminar forced convection, and turbulent forced convection flows. While the results obtained in the laminar cases confirm only the technique, the results obtained in turbulent flow not only agree with past experiments but also extend our understanding of the near-wall flow field. The results show spanwise nonuniformities in heat transfer coefficient which manifest themselves as a streamwise streaky structure similar to those seen in the hydrodynamic sublayer of turbulent boundary layers.* Although measurements of heat transfer in concave curvature have yet to be made, the apparatus was on the verge of operation at the date of this report. Application of the technique to surfaces with holes has been studied, in preparation for studies of full-coverage film cooling.

Control Console

The control console which supplies power to the 14 heaters has been completed. It allows individual control and measurement of power to each of the 14 panels in the test wall. A single digital wattmeter is used to measure the plate power from all the heaters by means of switch selectable relays. The wattmeter has been interfaced to a digital computer to provide online data-acquisition capability. Software has been written. The system is now operational.

Preheater Plates

In order to eliminate the undesirable effects of unheated starting length, four silicone rubber preheater plates were designed for the heat transfer rig. Each was coated with a sheet of liquid crystal. While these heaters will not be used to accurately measure heat transfer, the liquid crystal color and therefore temperature will be used as a guide for setting up an isothermal test surface upstream of the measurement plates.

Heat Flux Uniformity Tests

Tests showed there was considerable variation from one bus bar to the another in heat release from the gold film heaters. It was therefore deemed desirable to measure the uniformity of all pieces used in the final construction. Our established technique for uniformity measurement was prohibitively time consuming for all but spot checks; therefore, a faster measurement tech-

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*First documented under predecessor AFOSR contracts.

nique was devised. A small DC voltage was applied across the two copper bus bars attached to the gold film, setting up a potential field in the gold film. A four-pronged probe with four equally spaced, graphite-tipped sensors was used to measure voltage differences between 1 inch centers. The probe was traversed across the gold sheets manually. Voltages from the traverse were recorded with the aid of an online computer system. The results were plotted on a 3-D plot as shown in Fig. II-B1. This technique was considerably faster than the previous one.

Computer Modeling

During the past year, work has begun on a computer model for concave curvature effects. A mixing length modification to the basic STAN5 computer program is employed. A simple model for concave curvature was inserted into the program. Several data sets from previous experiments have been evaluated. Work on evaluating the constants in the model is currently underway.

Laminar Forced Convection Qualification

Calibration tests have been completed in a 6 degree wedge, laminar forced convection flow. A single, waterproof liquid crystal package was mounted in a flat plate rig and installed in the water channel. The results of a typical case are shown in Fig. II-B2. The broad white band is the liquid crystal contour line representing a value of heat transfer coefficient, $h = 739\ W/m^2\ C$. Also shown in the figure are three lines which show the location of $h = 739\ W/M^2\ C \pm 10\%$ as predicted by STAN5. The agreement between the two methods is excellent.

Turbulent Forced Convection Tests

The technique was also qualified in a flat plate, zero pressure gradient, turbulent boundary layer. Three liquid crystal packages were mounted in the water channel in the region upstream of curvature. The average heat transfer results are plotted in Fig. II-B3. The solid line represents the STAN5 prediction for this flow. There are three sets of experimental points obtained for each plate. The lowest Stanton number points represent the points where the first indication of green (the calibration color) is present on the plate. These green streaks represent the low speed, high temperature streaks. The highest Stanton number points, on the other hand, are the last green present on the plate. In this case, the streaks represent high speed, low temperature streaks. The middle data points represent the place where the maximum amount of surface is covered by green. By the use of this technique, some indication of the amplitude of heat transfer coefficient fluctuations is apparent.

A photograph of the surface of a typical plate is shown in Fig. II-B4. The complexity of the local, surface heat transfer is readily apparent. It should be pointed out that all of this information would be lost in conventional measurement techniques which average the heat transfer in both the spanwise direction and in time. A simple technique for digitizing a photograph of the surface heat transfer has been devised. It uses an infrared sensor traversed across a photograph with a computer controlled digital x-y plotter. A sample result of the photograph of Fig. II-B4 is shown in Fig. II-B5. The spanwise spacing of the streaks has been measured and was found to be 100 in inner wall coordinates. This is in agreement with previous results obtained with surface dye injection and hydrogen bubbles.

Correction for Hole in Heater

The technique as originally developed was only useful for continuous surfaces. If a hole were cut into the gold film heater, the heat flux would be severely distorted in the region around the hole. This distortion can be corrected by employing a conductive ring around the circumference of the hole. In the case of a circular hole, the resistance per unit length of the conductive ring was found to be constant and equal to the resistivity of the heater divided by the radius of the hole. A demonstration of the effectiveness of this technique was carried out numerically. Laplace's equation was solved over one quadrant of a circular hole using 337 nodes. Fig. II-B6 shows isopotential lines for two cases. The smooth lines show the case with no conductive ring, while the dashed lines represent the case employing a conductive ring. The use of a conductive ring is seen to work very well.

Although this technique has been demonstrated for a circular hole, in principle a hole of any shape could be accomodated. The resulting resistance per unit length may not be constant nor easily predictable analytically, but it could, at worst, be found numerically.

Work in Progress

The fabrication of the 7 straight, liquid crystal packages for installation into the regions upstream and downstream of curvature has been completed. The fabrication of curved packages for installation into the concave region is 90% complete. Once this has been completed, heat transfer measurements in the curved region will begin.

Publications completed during 1980-81

II-B1 "A new Technique for Mapping Heat Transfer Coefficient Contours", by J. C. Simonich and R. J. Moffat, accepted for publication by The Review of Scientific Instruments, scheduled for May, 1982 publication.

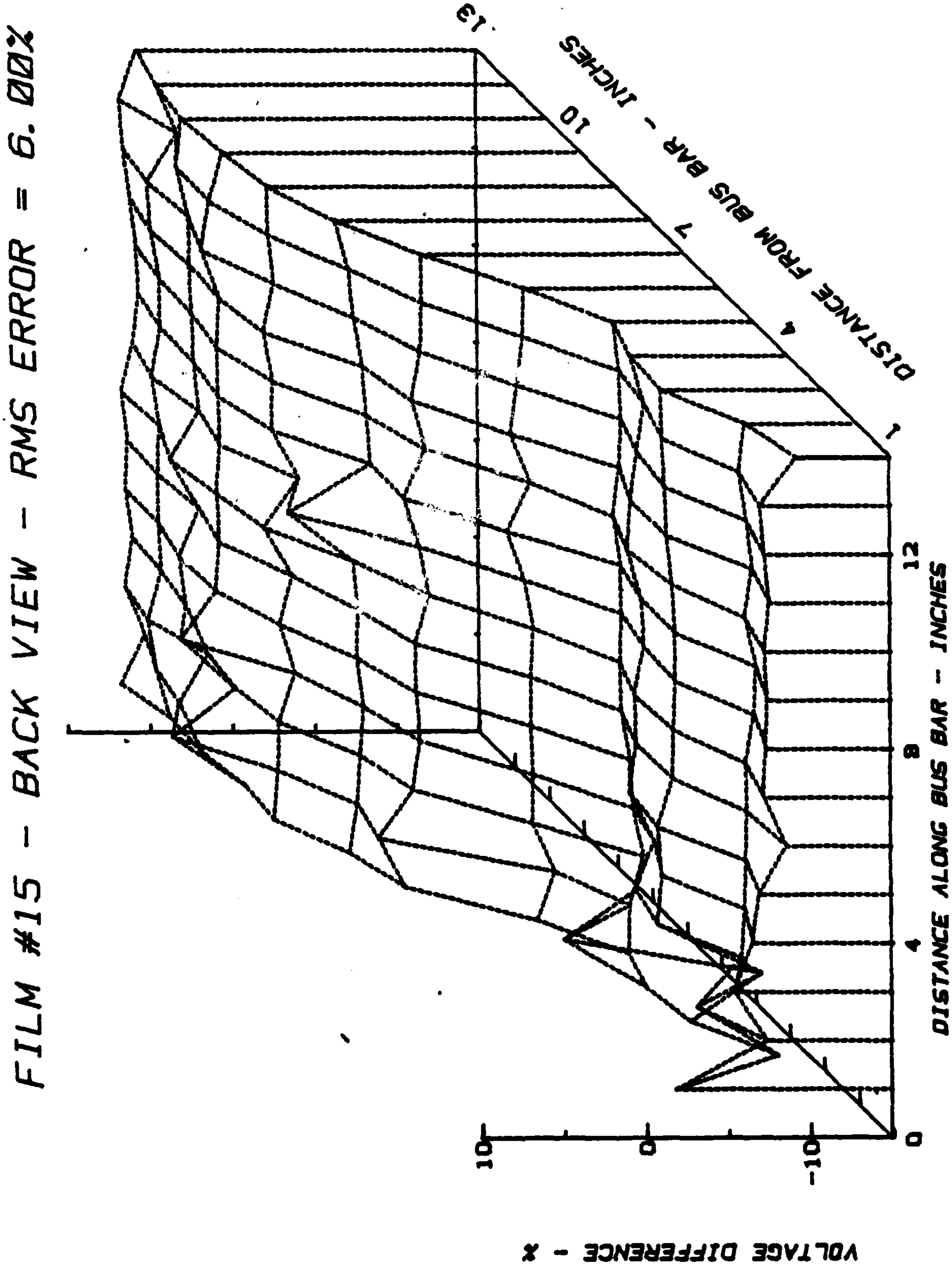
FILM #15 - BACK VIEW - RMS ERROR = 6.00%
DISTANCE FROM BUS BAR - INCHES
1
4
7
10
13
DISTANCE ALONG BUS BAR - INCHES
0
4
8
12
VOLTAGE DIFFERENCE - %
10
0
-10

Figure II-B1

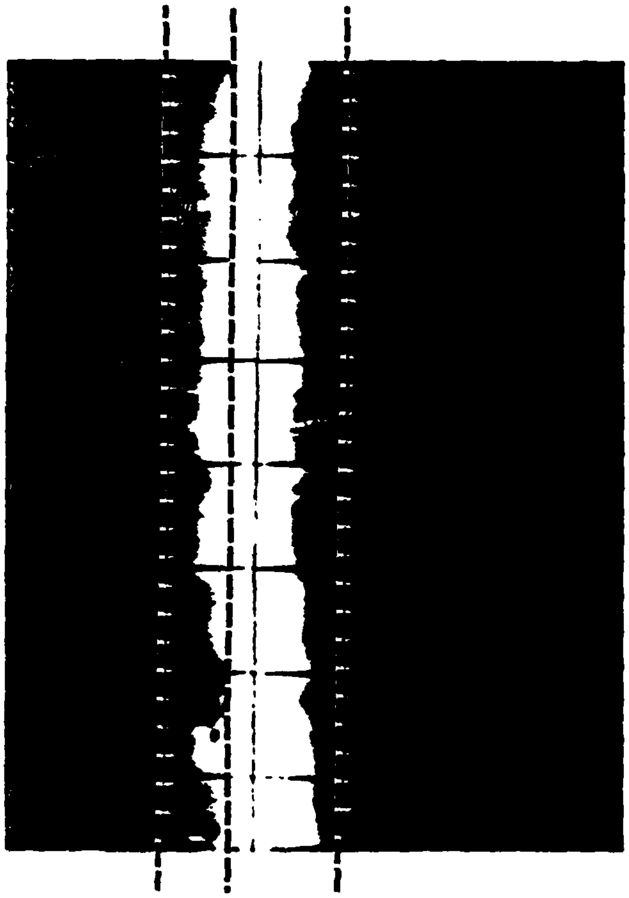

Figure II-B2

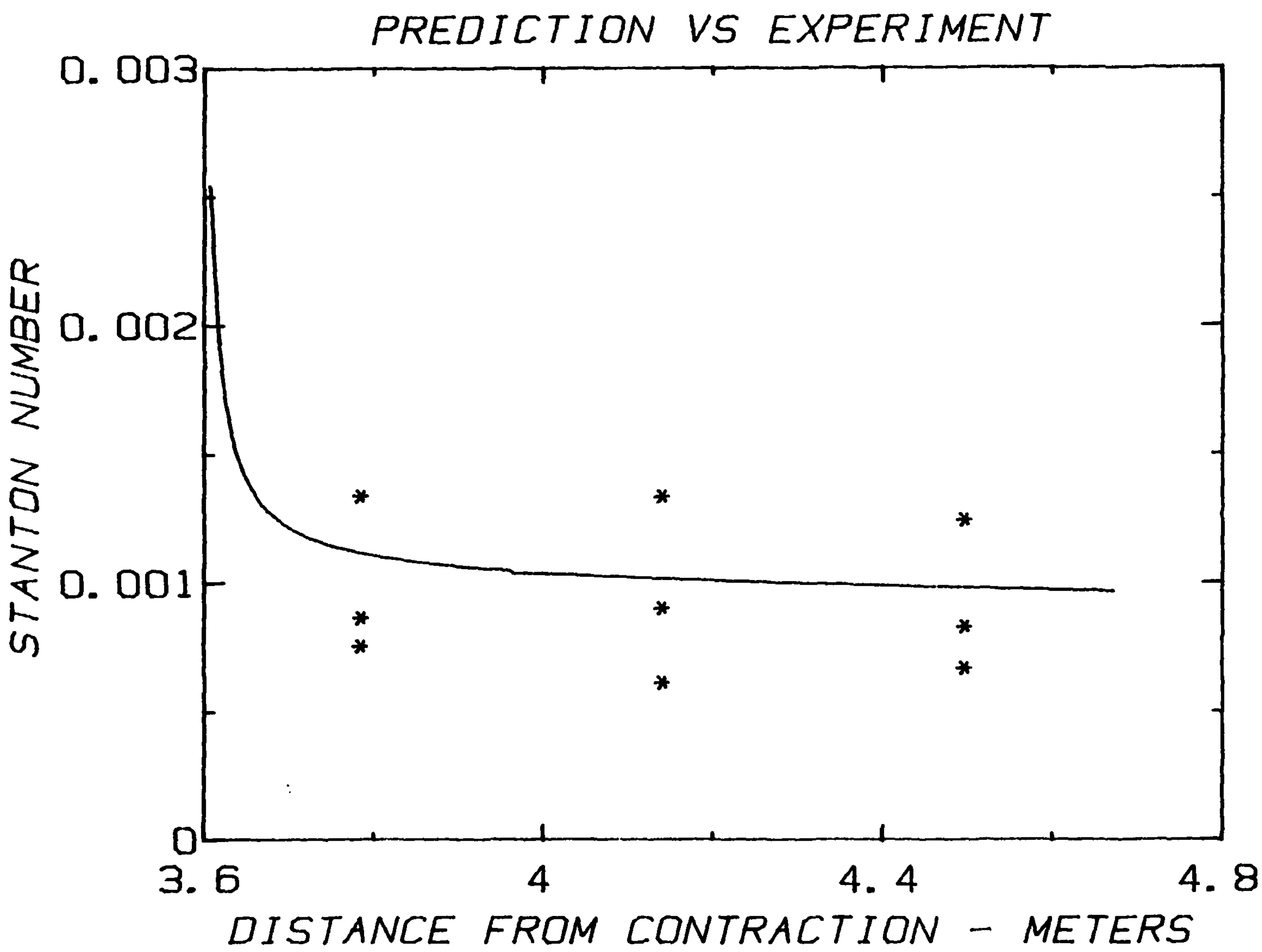
PREDICTION VS EXPERIMENT
0.003
0.002
0.001
0
3.6
4
4.4
4.8
STANTON NUMBER
DISTANCE FROM CONTRACTION - METERS
Figure II-B3

Figure II-B4

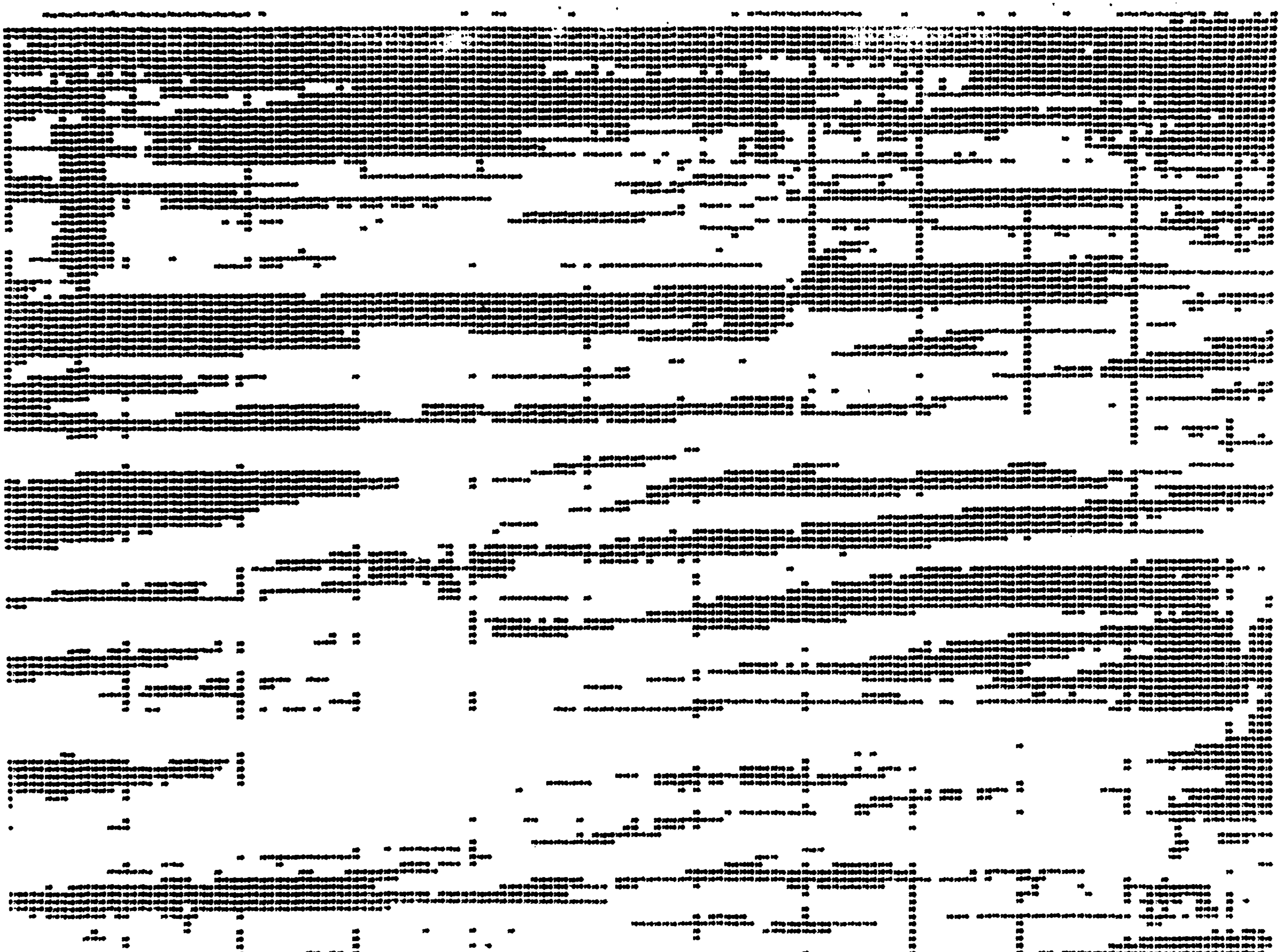

Figure II-B5

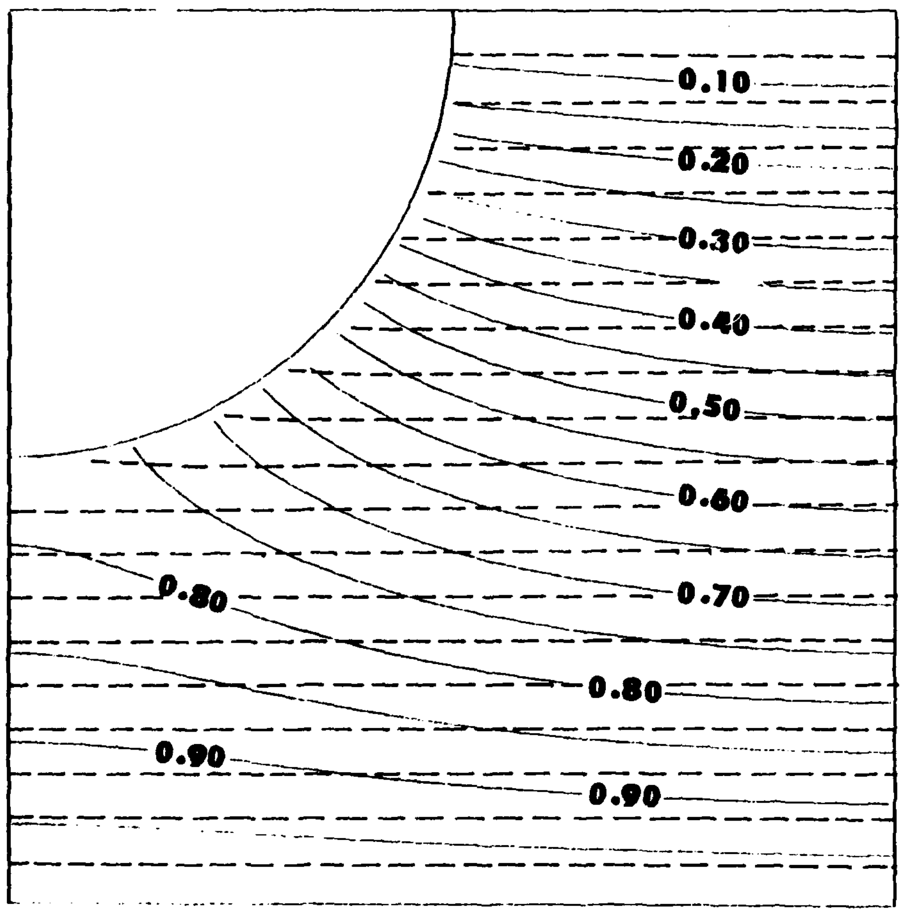

Figure II-B6

3. Status of Research, Part II (cont.)

C. ADVANCES IN MULTIPLE HOT-WIRE ANEMOMETRY*

Principal Investigator: R. J. Moffat

Research Assistant: Mauricio N. Frota

Current Status:

A four-wire, hot-wire system has been developed which measures the instantaneous values of the velocity components, corrected to account for the local fluid temperature. Turbulence quantities are calculated in real time by high-speed analog devices without invoking the "low-turbulence assumption"; this eliminates the time-averaging ambiguities present in the rotatable slant-wire approach.

Three mutually orthogonal wires suffice to solve the hydrodynamics in flows whose temperature is uniform. In this case, the mean velocity and the turbulent shear-stress component, $\overline{u'v'}$, can be measured within 1.4% and 4.8%, respectively, so long as the velocity vector lies within 20° of the probe axis. No reference flow is available for calibrating the remaining components of the Reynolds stress tensor, but the values returned by the Triple-Wire Processor are in agreement with prior results using different techniques.

This high overall system accuracy was obtained by using the overheat controls of each channel to compensate for small but critical channel-to-channel differences in response and also to compensate for changes in temperature level.

Addition of a fourth wire permits measurement of temperature fluctuations and/or data acquisition in heated flows. The temperature-compensation circuitry has been fabricated and tested. The compensated velocity signals remained accurate within 2% over a change in fluid temperature from 18 to 32°C. The analog devices used in the overall circuitry were shown to produce less than 2° phase shift and less than 0.1% attenuation over the frequency range from DC to 20,000 Hz. Temperature fluctuations up to 3 kHz should be accurately handled by the circuit, based on the response characteristics of a 1-μm wire used as the temperature sensor. This thermal frequency response seems adequate for laboratory-scale boundary layer work. The system has not yet been tested in a non-isothermal flow.

A purely analytical investigation of the uncertainties associated with the triple hot-wire equations is completed. This analysis shows that the residual uncertainty present in the output of the triple-wire processor is a natural consequence of probe-manufacturing tolerances. The size of the probe, relative to the velocity gradient, is shown to be an important source of spurious signals.

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*Primarily supported from Affiliates funds and NASA-Lewis contract for work on turbulent boundary layer on convex wall.

Exact equations have been derived for the sensitivity coefficients of the three instantaneous velocity components with respect to each one of the variables involved. These equations were derived using the MACSYMA Multiaccess Computer System (the MC-Machine at the Laboratory for Computer Sciences, M.I.T.).

Absolute and relative uncertainties for the instantaneous triple hot-wire outputs have been calculated, based upon a random combination of uncertainties in all inputs. These have been calculated as a function of roll and pitch angles.

Results show that the uncertainty band associated with measurements of the streamwise velocity component is on the order of 2%, regardless of roll and pitch. Uncertainties associated with the V and W channels are sensitive to both roll and pitch angles and are on the order of 2% and 4%, respectively, when the probe is aligned with the flow. These uncertainties reach ±5% at 20° misalignment, and are not symmetrical with respect to pitch.

In addition to evaluating the stochastic component of the uncertainties, this analysis has also allowed prediction of the deterministic components (fixed errors) present in some of the outputs. Comparison between computation and data, taken in a channel flow (Fig. 1) and in a thin boundary layer flow (Fig. 2), shows that the fixed errors (spurious signals) present in the V and W channels of the triple wire output are due to the finite measuring volume of the triple-wire probe.

A similar uncertainty analysis on a new triple hot-wire approach recently suggested in the literature (Acrivlellis, 1980) was also completed. In this new scheme the probe is easy to fabricate, since all three wires are in the same plane. On these grounds, the design is very attractive. The method becomes very uncertain, however, as a consequence of the data-reduction equations. Uncertainties associated with measurements of U, V, and W were found to be as high as 3%, 53%, and 67%, respectively, even if the probe was aligned with the flow. This calculation illustrates the fact that the technique of uncertainty analysis used (Refs. II-C4, C5, C11) has proved to be a useful tool in the design stage of a new instrument or experiment of engineering importance and may save considerable time and cost. This analysis can be used as a design criterion, since it sets the basis for the treatment of the overall accuracy desired.

Reports and Papers Available Related to This Topic:

II-C1 "Analog Multipliers for Turbulence Structure Measurements," HTTM Report IL 46.

II-C2 "Effect of Combined Roll and Pitch on the Measurements of a Mean-Velocity and reynolds Stresses by Means of a Triaxial Probe," HTTM Report IL 22.

II-C3 "Instrumentation for Measurements of Turbulence Components in a Three-Dimensional FLow Field," AFOSR-TR-790957.

II-C4 The Triple Hot-Wire Equations and Related Sensitivity Coefficients," HTTM Report IL 37.

II-C5 "Temperature Compensation for Hot-Wire Anemometry," HTTM Report IL 47.

II-C6 Frota, M. N., and Moffat, R. J., "Effect of Combined Roll and Pitch Angles on Triple Hot-Wire Measurements of Mean and Turbulence Structure," to appear in DISA Bulletin, DISA Information, 1982.

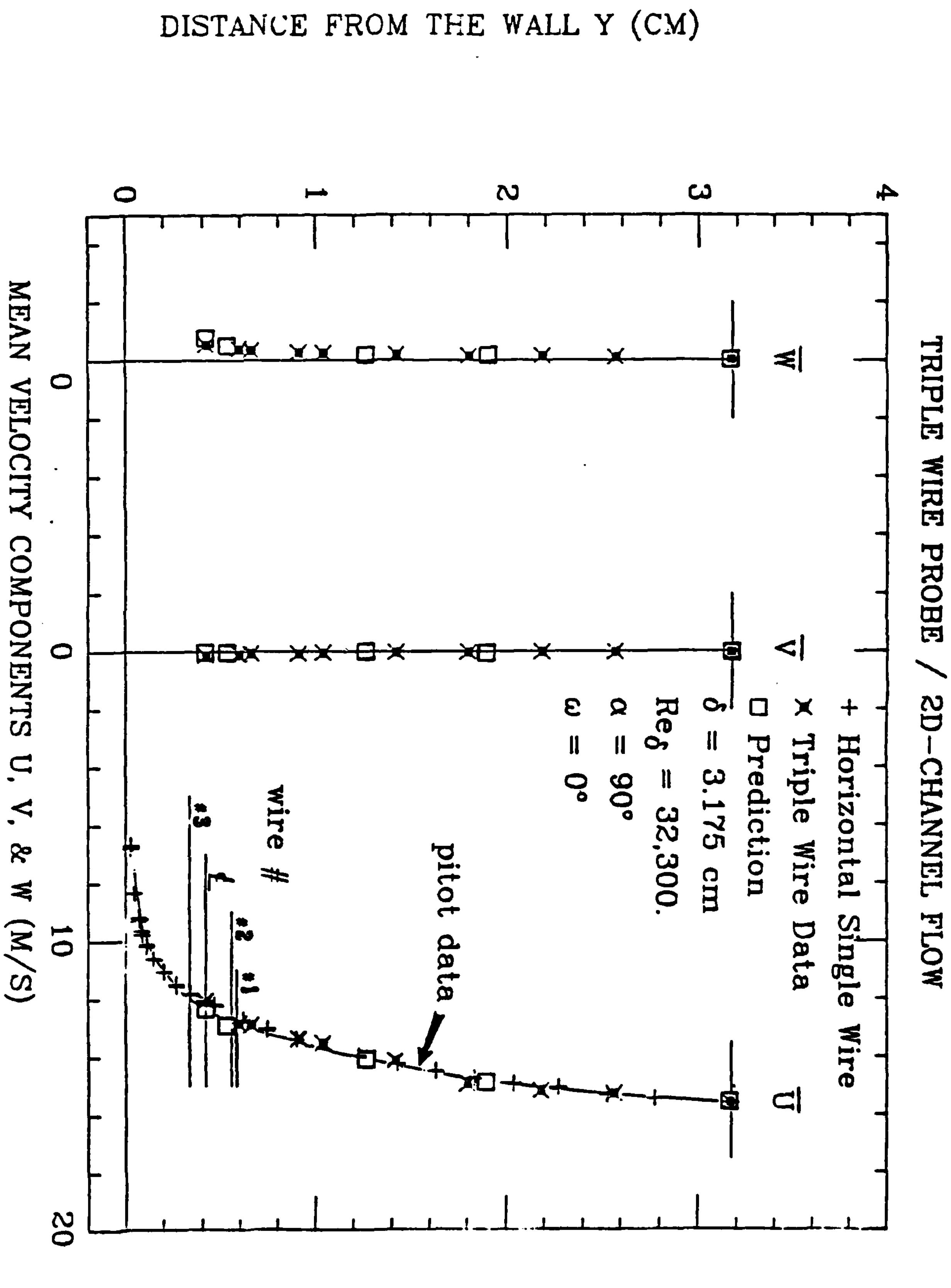
II-C7 Frota, M. N., and Moffat, R. J., "Triple Hot-Wire Technique for Measurements of Turbulence in Heated FLows," submitted to the 7th International Heat Transfer Conference, Munich, West Germany, Sept. 6-12, 1982.

II-C8 Frota, M. N., and Moffat, R. J., "flow Disturbance Induced by the DISA Triaxial Hot-Wire Probe 55P91," to appear in DISA Bulletin, DISA Information, 1982.

II-C9 Frota, M. N., and Moffat, R. J., "Advances in Triple Hot-Wire Technique for Measurements of Turbulence Structure," Proceedings of the COBEM 81, the VI Congresso Brasileiro de Engenharia Mechanica, Rio de Janeiro, R. J., 15-18 Dez. 1981.

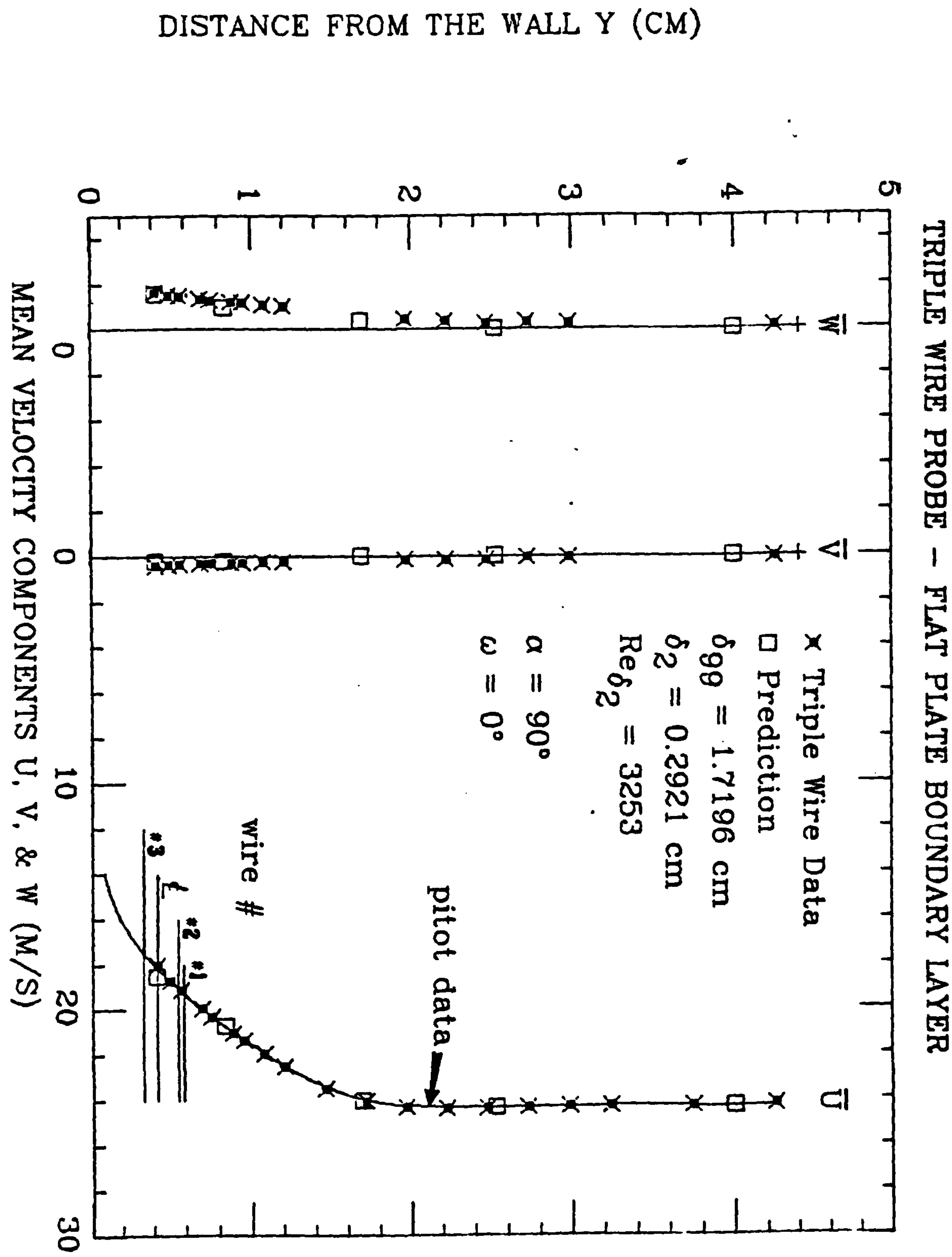
II-C10 Frota, M. N., and Moffat, R. J., "Analysis of the Uncertainties in Velocity Measurements with Triple Hot-Wire Probe," paper to be presented at the XIV International Centre for Heat and Mass Transfer Symposium on Heat and Mass Transfer in Rotating Machinery, to be held at Dubrovnik, Yugoslavia, Aug. 30-Sept. 3, 1982.

II-C11 Moffat, R. J., "Some Contributions to the Theory of Uncertainty Analysis," in Vol. I, Procs. of the 1980-81 AFOSR-HTTM-Stanford Conference on Complex Turbulent Flows. Also to be published in the Journal of Fluids Engineering with further discussions by R. Abernethy, S. Kline, and R. Dowdell.



TRIPLE WIRE PROBE / 2D-CHANNEL FLOW
+ Horizontal Single Wire
x Triple Wire Data
□ Prediction
δ = 3.175 cm
Re$_δ$ = 32,300.
α = 90°
ω = 0°
pitot data
wire #
#1
#2
#3
℄
W̄
V̄
Ū
DISTANCE FROM THE WALL Y (CM)
MEAN VELOCITY COMPONENTS U, V, & W (M/S)
0
1
2
3
4
0
0
10
20

Figure II-C1



TRIPLE WIRE PROBE – FLAT PLATE BOUNDARY LAYER
DISTANCE FROM THE WALL Y (CM)
MEAN VELOCITY COMPONENTS U, V, & W (M/S)
Triple Wire Data
Prediction
δ_{99} = 1.7196 cm
δ_2 = 0.2921 cm
Re_{δ_2} = 3253
α = 90°
ω = 0°
wire #
pitot data
#3
#2
#1
$\bar{W}$
$\bar{V}$
$\bar{U}$
0
1
2
3
4
5
0
0
10
20
30

Figure II-C2

3. Status of Work (cont.)

IV. Special Comment

The completion of Professor R. J. Moffat's work on "Uncertainty Analysis" merits special comment.

The paper by Prof. Moffat was encouraged by and in part edited by Prof. S. J. Kline, who has a long-standing interest in this area of work. While the work is not listed as an official part of the AFOSR contract, it underlies and is stimulated by many facets of the work for AFOSR.

In the opinion of Prof. S. J. Kline, Prof. Moffat's paper is the first major conceptual advance in the analysis of uncertainty in single-sample experiments since the seminal paper of Kline and McClintock (Mech. Engrg., Jan. 1953). The Kline-McClintock paper has for some years served as the standard, and its use is a requirement for publication of experimental work in some journals (e.g., J. Fluids Engrg.).

Most engineering experiments are single-sample in at least some important aspects, and hence not amenable to verification via standard procedures of statistics. It was that fact which led to the work of Kline and McClintock. Over the intervening years, since that paper appeared, no other method for this application has been published.

Moreover, experience over the years shows that whenever the Kline-McClintock procedure has been carefully applied to an experiment of any degree of complexity, a clearer vision of how to run the experiment effectively is achieved, and a much tighter estimate of the utility (accuracy) of output is realized.

As noted by R. Abernethy, the Kline-McClintock procedure has served as the underlying conceptual structure for many of the codes and standards in ASME and has been the basis for erection of standard test calibrations for facilities of import to USAF (for example, in acceptance testing jet engines at more than one facility to ensure conformance with specifications).

Despite these gains, certain problems remained in 1980. (i) No procedure was given in the Kline-McClintock paper for use with computer data reduction, since it was virtually unknown in 1953; (ii) the problem of fixed errors was not completely handled in the Kline-McClintock paper. Conceptualization of fixed errors remained a vexing problem that caused prolonged discussions in code committees and other places. (iii) Some types of engineers used the procedures; others did not.

All these facets came sharply under review at two points in 1980. First, Prof. F. M. White, current editor of the Journal of Fluids Engineering, noted that some papers were submitted with "eyeball estimates" rather than complete analyses of uncertainty, and so reported to the Executive Committee of the Fluids Engineering Division of ASME. The Executive Committee then arranged a panel moderated by Prof. White, consisting of Prof. R. J. Moffat, Prof. k. Dowdell, Mr. R. Abernethy, and Prof. S. J. Kline at the Winter Annual Meeting of ASME in Washington, D. C., Nov. 1980.

As a result of this panel, Prof. S. J. Kline recommended to the Executive Committee of the Fluids Engineering Division (of which he is himself a past chairman) that they approve a new requirement for publication of experimental papers in JFE, namely, that a complete uncertainty analysis be submitted with the paper. This analysis would not be for publication, but would rather be for the information of the reviewers. Action on this item has not yet occurred.

Similar discussions surfaced in the 1980 meeting of the AFOSR-HTTM-Stanford Conference on Complex Turbulent Flows. It became clear in that meeting that, while mechanical engineers had in general used uncertainty analysis, aero/astro engineers had not. It also became clear that much data was less valuable as a basis for constructing models and comparing with output of computations precisely because the uncertainty analyses had not been done, and hence reliable estimates of accuracy, which is vital to the comparisons, were not available.

The current paper by R. J. Moffat answers the questions raised by items (i) and (ii) above, and in doing so defines an appropriate level of uncertainty estimate as a control on experimental verification at each of three stages of work: (i) in design, (ii) during check-out and debugging, and (iii) in comparing results from one lab with those from another or in comparing data and computation. Professor Moffat emphasizes the use of these "controls" as a feedback verification procedure. Moffat's paper also provides a very simple, explicit procedure for use in data reduction by computer that provides a guarantee against taking data in some range of the test-parameter hyperspace where uncertainties aggregate to high values.

As Prof. S. J. Kline notes in the discussion of Moffat's paper for JFE, the widespread use of the concepts of uncertainty analysis as extended in Moffat's paper as a requirement for the publication of experimental work would in a relatively short time do more to improve the accuracy and meaningfulness of experimental output than anything else known at the present time. This follows from the fact that careful application of uncertainty analysis brings an improved understanding of (i) the critical measurements; (ii) instrument needs; (iii) experimental control in the broadest sense. Moreover, this has been true in every case where the procedure has been carefully applied.

The preceding paragraph does not imply that the procedure of uncertainty analysis is automatic or can be applied without thought. Just the opposite is true. The procedure enforces hard thought about the experiment and the data reduction procedures in a way that leaves no loopholes behind when the method is correctly employed. It is precisely this enforcement of hard, detailed thought at the appropriate points in time that makes uncertainty analysis useful.

Professor Moffat's paper not only brings even sharper tools for various stages of experimental work but also appropriately focuses attention on feedback, that is, on a check that pre-estimated values of uncertainty are in fact produced in the data-taking processes. If they are not reproduced, an investigation is set in motion to discover the cause(s) of the discrepancy.

Uncertainty analysis is often resisted by experimenters on the grounds that it is too hard, or unnecessary. In our experience, it is always necessary in any experiment of any sophistication, in which results are intended for record and not merely as exploratory. The time spent repays the effort many times over in nearly every instance.

In sum, it seems time for many societies and branches of engineering to reconsider the current stands with regard to requirements for uncertainty analysis as a precondition for publication. Adoption of such a standard would within a few years create a major improvement in the quality of experimental work in the United States and thereby increase the value received on many U.S. Government contracts.

Publications during 1980-81 Period

1. "A Prediction Method for Planar diffuser Flows," by J. Bardina, A. Lyrio, S. J. Kline, J. H. Ferziger, and J. P. Johnston; J. Fluids Engrg., Trans. ASME, Vol. 103, pp. 315-321, June 1981.

2. "Measurement, Correlation, and Computation of Detachment and Reattachment of Turbulent Boundary Layers on Faired Surfaces," S. J. Kline, J. G. Bardina, A. Strawn, presented at AIAA meeting, Palo Alto, CA., June 1981. To be published in AIAA Journal.

3. "Summary of AFOSR/MSU Research Specialists' Workshop on Coherent Structures in Turbulent Boundary Layers: July 30-August 1, 1979," S. J. Kline and R. E. Falco. (Report CSL-80-1; issued by Michigan State University. Draws extensively on AFOSR-sponsored work at Stanford.)

4. "The Effects of Concave Curvature on Turbulent Boundary Layers," A. H. Jeans and J. P. Johnston at Am. Physical Society, Div. of Fluid Dynamics, November 23-26, 1980.

5. "Some Contributions to the Theory of Uncertainty Analysis," R. J. Moffat, Vol. I, Proc. AFOSR-HTTM-Stanford Conference on Complex Turbulent Flows. presented at Panel of the ASME Winter Annual Meeting, Nov. 1981, Washington, D. C., and to appear with added discussion by R. Abernethy, R. Dowdell, and S. Kline in J. Fluids Engrg.
Special comment (by S. Kline): This is an important contribution. See special comment by S. Kline under Section 3-IV: Special Coment above. For illustration of importance in application of concepts, see Section 3-III above.

Reports and Papers Completed During 1980-81

5. "Effects of Concave Curvature on Turbulent Boundary Layer Structure," A. Jeans and J. P. Johnston.

6. "A Stall Margin Method for Planar and Axisymmetric Diffusers," R. C. Strawn and S. J. Kline, submitted to J. Fluids Engrg. (See also item 10.)

7. PD 22 Bardina, J., Computation of Straight Diffusers at Low Mach Number Incorporating an Improved Correlation for Turbulent Detachment and Reattachment, Thermosciences Div., Dept. of Mech. Engrg., Stanford University, Stanford, CA 94305. (1982)

8. PD 23 Lyrio, A. A., Ferziger, J. H., Kline, S. J., An Integral Method for the Computation of Steady and Unsteady Turbulent Boundary Layer Flows, Including the Transitory Stall Regime in Diffusers, Thermosciences Div., Dept. of Mech. Engrg., Stanford University, Stanford, CA 94305. (1981)

9. PD 24 Childs, R. E., Ferziger, J. H., Kline, S. J., Johnston, J. P., A Computational Method for Compressible Planar Diffusers, Thermosciences Div., Dept. of Mech. Engrg., Stanford University, Stanford, CA 94305.

10. PD 25 Strawn, R. C., Kline, S. J., A Stall Margin Design Method for Planar and Axisymmetric Diffusers, Thermosciences Div., Dept. of Mech. Engrg., Stanford Unviersity, Stanford, CA 94305. (1981)

Note regarding items 6-10. As reported previously these five reports together provide an excellent, fast solution to the problem of design of most applications for diffusers with straight centerlines, near potential inlet flow and small dissipation on the center streamline to exit. Work has therefore moved onto the next class of problems.

5. Professional Personnel Associated with the Project

Faculty: Prof. S. J. Kline, Prof. J. H. Ferziger Prof. J. P. Johnston, Prof. R. J. Moffat, Dept. Mech. Engrg.

Visitors: Prof. Y. Nagano, Nagoya Institute of Technology (work on wall probes)

Research Assistants (all Ph.D. Candidates):

J. G. Bardina, A. Lyrio, R. Childs, R. Strawn (work on diffuser computations, correlation of detachment and reattachment).
S. Pronchick (work on reattachment, back-step).
A. Jeans (Hydrodynamics on concave wall).
J. Simonich (Heat transfer on concave wall).

Closely related projects and contributors to ongoing research include:

Professor J. K. Eaton (work on instruments; developer of thermal tuft and wall-shear probes; work on reattachment zone in air--compliments water study)

Research Assistants
E. Adam
A. Cutler (diffuser inlet conditions)
P. Eibeck
J. Vogel
R. Westphal

6. Interactions, Honors, Speeches

Professor S. J. Kline was elected a member of the National Academy of Engineering and also awarded the ASME Centennial Medallion.

Active dissemination of results to 21 industrial companies through the Thermosciences Affiliates Conference and of reports to 200-400 individuals using Affiliates funds continues.

Nearly all doctoral candidates in HTTM participated as technical recorders and aides in the 1980-81 AFOSR-HTTM-Stanford Conference on Complex TUrbulent Flows. A few assisted in preparing taxonomies of models or numerics or in creating data for predictive test cases. These efforts not only were important for the Conference but also were an important educational opportunity for the students.

7. New Discoveries, Inventions, Patent Applications

No new patents were filed during 1979-80.

See special comment in Section IV-B above.

8. Other Information

The very rapid progress in diffuser computation, optimization, stall margin calculations, and on the physical understanding of flow detachment during 1979-80 is a culmination of accumulating pieces of new knowledge and techniques going back to the early 1970s. They combine not only wholly new knowledge and methods, but also a number of minor improvements and fine-tunings that collectively have important impact on the speed and accuracy of computation.

DATE

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